

Privacy-Preserving English Auction Protocol with Round Efficiency

Hu Xiong^{a,b,*}, Zhong Chen^a

^aSchool of Electronics Engineering and Computer Science, Peking University, Beijing, P.R.China

^bSchool of Computer Science and Engineering, University of Electronic Science and Technology of China, P.R.China

Abstract

A privacy-preserving English auction protocol with round efficiency based on a modified ring signature has been proposed in this paper. The proposed protocol has three appealing characteristic: First, it offers *conditional privacy-preservation*: on the one hand, the bidder is anonymous to the public, on the other hand, only the collaboration of auctioneer and registration manager can reveal the true identity of a malicious bidder. Second, it *does not require to maintain a black list* which records the evicted malicious bidders. Finally, it is *efficient*: it saves the communication round complexity comparing with previously proposed solutions.

Keywords:

English auction; Conditional anonymity; Round efficiency; Ring signature

1. Introduction

Electronic auctions are a very popular trading method for determining a customer and the sale price [17]. They are not only widespread mechanisms to sell goods, but have also been shown applicable to task assignment, scheduling, or finding the shortest path in a network with selfish nodes [6]. According to the goals and decision strategies, the electronic auction protocols can be categorized into the sealed-bid auction [22, 16, 33], the English auction [14, 17], and the $(M + 1)$ st-price auction [2, 6]. In an English auction, each bidder offers the higher price one by one, and finally a bidder who offers the highest price gets the desired goods. It is noted that all bid values are published and any bidder easily knows the price position of goods in English auction. Therefore, a bidder has the dominant strategy for bidding, which places a little higher than a current bid value. In this way, the competition principle well works and the winning bid value reflects a market price. This is why an English auction is the most familiar style of auctions. Therefore, this study focuses on the English auction protocol, bringing up related issues and methods.

Privacy is a crucial issue in designing the auction protocols. A major reason why people may be hesitant to participate in auction protocol themselves, is the worry that too much of their private information is revealed. Furthermore, in the modern electronic society, the information

*Corresponding author

Email address: xionghu@pku.edu.cn (Hu Xiong)

might get propagated to large numbers of parties, stored in permanent databases, and automatically used in undesirable ways. To solve this problem, we study the possibility of designing the English auctions with communication round efficiency in a way that preserves the bidders' privacy. Franklin and Reiter [16] were among the first researchers to address electronic auction with bid privacy. They covered many problems such as secret sharing, digital cash and multi-cast as well as their own primitive technique called verifiable signature sharing. Their protocol successfully prevents a single auctioneer from altering a bid or throwing an auction to a single bidder. Unfortunately, in their protocol, all bids will be disclosed to all auctioneers after the auction is closed. Kikuchi *et al.* [20] attempted to deal with such problems through secret sharing techniques, but Sako [28] pointed out that several problems still remain in their work. Also, there are protocols where bidders themselves jointly compute the auction outcome without relying on trusted third parties at all [6, 7]. The main advantage of these protocols is that they are fully private, *i.e.*, when relying on computational intractability assumptions, no coalition of parties is capable of breaching privacy. The drawbacks implied by such a model are low robustness and relatively high computational and communication complexity. Chang *et al.* [12] and Jiang *et al.* [18] proposed anonymous electronic auction protocols based on the deniable authentication. Nevertheless, in these protocols, the auctioneer must verify the identity and bid price of all bidders one by one during the bidding stage to ensure the legality of a bidder and the integrity of the bid price. So these protocols will pose a heavy computation overhead for the server at the auctioneer's end. Omote *et al.* [25, 26] initially proposed electronic English auction which realize both anonymity of bidders and traceability by employing bulletin boards. However, their method does not publicize bidder information because publishing such information compromises privacy, including anonymity, fairness and non-linkability among various auction rounds, etc. Sakurai *et al.* [30], Nguyen *et al.* [24] and Lee *et al.* [22] proposed anonymous and non-repudiate auction protocols based on group signature respectively. Although they realized the privacy-preserving auction protocol efficiently, the auction manager have to maintain a *black list*, which is the list of participants that have their memberships revoked. Hence, each bidder has to spend additional time on verifying whether the other bidders had been revoked or not. Furthermore, when the number of revoked members in the black list is larger than some threshold, the protocol requires every remaining bidder to renew their secret membership key and updating public information. To solve this problem, Xiong *et al.* [33] proposed an anonymous auction protocol based on the ring signature, where the bidder can be easily removed from the system. Whereas, taking round efficiency into consideration, Xiong *et al.*'s protocol is much more costly than the previously protocols.

In this paper, we propose an English auction protocol with privacy-preserving based on revocable ring signature [23]. In addition to satisfy the above properties, our protocol has the following unparalleled features: (a) The proposed protocol can efficiently evict the malicious bidder instead of maintaining the black list or updating the public information; (b) Our protocol has low round communication complexity.

The remainder of this paper is organized as follows. The next section presents background information related to English auction protocol. Section 3 details the proposed auction protocol, followed by the security analysis and the performance analysis in Section 4. Section 5 concludes this paper.

2. Preliminaries

2.1. Desired requirements

Recently, the need for privacy has been a factor of increasing importance in auction design and various schemes to ensure the safe conduction of English auctions have been proposed [6, 7, 14, 16, 17, 19, 20, 22, 24, 25, 26, 28, 29, 30, 33]. Meanwhile, any bid does not allow to be canceled in the case of English auction. Because the highest bid may be insignificant if a bid can be canceled in an English auction. Therefore, in an electronic English auction, it is the most important to satisfy the following two properties simultaneously: (a) Anonymity and (b) Traceability. Although any bidder can participate anonymously, it is necessary to identify a winner after the bidding phase without winner's help. This means that every bid placed in an English auction must be authorized while maintaining anonymity. In the following, we summarize the requirements of electronic auction from the researches of Chen[13], Chang and Chang[12], and Chung *et al.*[14], and Omote and Miyaji[25, 26]:

1. Anonymity: Nobody including the authority itself can identify the losing bidders even after the opening phase.
2. Traceability: The cooperation of registration manager (AM) and auction manager (RM) can identify the malicious bidder. In this way, the malicious bidder will be removed from the system. Note that an electronic auction has mainly two entities, the RM who treats the registration of bidders, and the AM who holds auctions.
3. Unforgeability: Nobody can impersonate a certain bidder.
4. Fairness: all bids should be fairly dealt with.
5. Public verifiability: Anybody can publicly verify that a winning bid is the highest value of all bids and publicly confirm whether a winner is valid or not.
6. Unlinkability among plural auctions: nobody can link the same bidders bids among plural auctions.
7. Robustness: Even if a bidder sends an invalid bid, the auction process is unaffected.
8. One-time registration: any bidder can participate in plural auctions by only one-time registration.
9. Efficiency: The protocol should be efficient from the viewpoints of computation and communication.

2.2. Bilinear Maps

Since bilinear maps work of composite order as the basis of our proposed scheme in this paper, we briefly introduce the bilinear maps [5] in this section. Let n be a composite with factorization $n = pq$. We have

- \mathbb{G} is a multiplicative cyclic group of order n ;
- \mathbb{G}_p is its cyclic order- p subgroup, and \mathbb{G}_q is its cyclic order- q subgroup;
- g is a generator of \mathbb{G} , while h is a generator of \mathbb{G}_q ;
- \mathbb{G}_T is a multiplicative group of order n ;
- $\hat{e} : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ is an efficiently computable map with the following properties:

- Bilinearity: For all $u, v \in \mathbb{G}$, and $a, b \in \mathbb{Z}$, $\hat{e}(u^a, v^b) = \hat{e}(u, v)^{ab}$.
- Non-degeneracy: $\hat{e}(g, g) = \mathbb{G}_T$ whenever $\langle g \rangle = \mathbb{G}$.
- $\mathbb{G}_{T,p}$ and $\mathbb{G}_{T,q}$ are the \mathbb{G}_T -subgroups of order p and q , respectively;
- the group operations on \mathbb{G} and \mathbb{G}_T can be performed efficiently; and
- bitstrings corresponding to elements of \mathbb{G} and of \mathbb{G}_T can be recognized efficiently.

2.3. Ring signature

Ring signature, introduced by Rivest, Shamir and Tauman [27], is characterized by two main properties: anonymity and spontaneity. Anonymity in ring signature means 1-out-of- n signer verifiability, which enables the signer to keep anonymous in these “rings” of diverse signers. Spontaneity is a property which makes distinction between ring signatures and group signatures [11, 4]. Group signature allows the anonymity of a real signer in a group to be revoked by a trusted party called group manager. It also gives the group manager the absolute power of controlling the formation of the group. Ring signature, on the other hand, does not allow anyone to revoke the signer anonymity, while allowing the real signer to form a group (also known as a ring) arbitrarily without being controlled by any other party. Since Rivest *et al.*’s scheme, many ring signature schemes have been proposed [9, 1, 31, 3, 15]. Inspired by the compact group signature[10], Shacham and Waters [23] proposed an efficient ring signature, which can be proved secure in the standard model. Also inspired by the group signature [10], we remark that the anonymity in this ring signature can be revoked by the trusted authority in the same way like [10]. That is to say, the signature allows a real signer to form a ring arbitrarily while allowing a trusted authority to revoke the anonymity of the real signer. In other words, the real signer will be responsible for what is has signed as the anonymity is revocable by authorities while the real signer still has the freedom on ring formation. In this paper, we propose a conditional privacy-preservation English auction protocol with round efficiency based on this modified ring signature scheme in [23].

3. The proposed English auction protocol

This section describes in detail our efficient privacy-preserving auction protocol. In a high level description, the auction system works as follows. To enrol in the system, each bidder contacts the registration manager and registers his own public key and corresponding real identity. (Through this way, the key escrow problem will be solved. That is to say, the registration manager can’t frame an innocent bidder by forging the bidder’s signature). After confirming the validity of bidder’s identity and public key, registration manager will publish the public key of the bidder on the Bulletin Board System (BBS). Each bidder collects the public keys of other bidders from BBS managed by registration manager. Then for each auction, a bidder can bid a value by generating a ring signature on the bid on behalf of this set of public keys. (We remark that the bidder’s public key must be included in this set of public keys). At the deadline, the identity of the bidder, who posts the highest bid, is retrieved using the revocation procedure. Bidder privacy is protected due to the anonymity and unlinkability properties of the underlying ring signature scheme.

The proposed scheme includes the following four phases: Initial phase, Bidding phase, Winner announcement phase, and Opening protocol. The notations used throughout this paper are

listed in Table 1. Let $B = \{B_1, \dots, B_l\}$ be a set of l bidders who take part in an auction and offer a price. Let RM be Registration Manager who manages the participants of auctions and AM be Auction Manager who holds an auction and opens the real identity of the bidder with RM. We assume that these two authorities RM and AM do not collude together. Figure 1 illustrates the auction procedure.

Table 1: Notations

Notations	Descriptions
RM:	Registration Manager who manages the participants of auctions by controlling the BBS.
AM:	Auction Manager who publishes $\{A, B_0, \hat{A}, u', u_1, \dots, u_k\}$ and keeps the tracing key $q \in \mathbb{Z}$ secret.
B_i :	bidder who has its own secret key $pk_i = g^{x_i}$ and public key $sk_i = A^{x_i}$, where $x_i \in_R \mathbb{Z}_n$
ID_i :	The real identity of the bidder B_i
$S = \{pk_1, \dots, pk_l\}$	l public key of corresponding bidders
M_i :	A bid generated by the bidder B_i
$\mathcal{H}_1(\cdot)$:	A hash function such as $\mathcal{H}_1 : \{0, 1\}^* \rightarrow \mathbb{Z}_n$
$\mathcal{H}_2(\cdot)$:	A hash function such as $\mathcal{H}_2 : \{0, 1\}^* \rightarrow \{0, 1\}^k$
$a \parallel b$	String concatenation of a and b

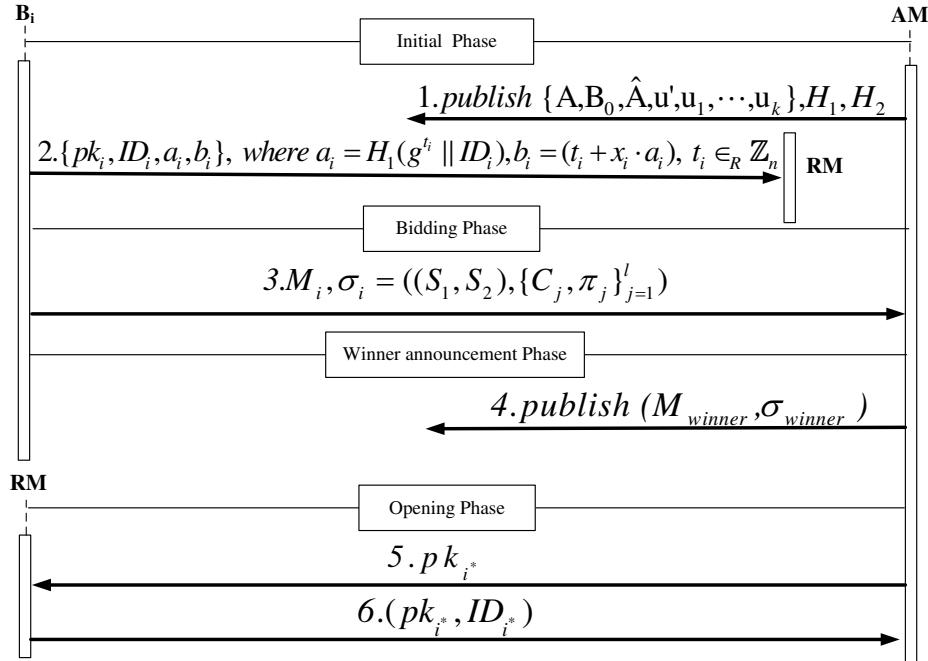


Figure 1: English Auction procedure based on Ring signature

3.1. Initial phase

Prior to the bidding phase, the AM sets up the system parameters and publishes it as follows:

The AM first constructs a group \mathbb{G} of composite order $n = pq$ as described in section 2.2 above. It then chooses exponents $a, b_0 \in_R \mathbb{Z}_n$ and sets $A = g^a$ and $B_0 = g^{b_0}$ and $\hat{A} = h^a$. Let $\mathcal{H}_1 : \{0, 1\}^* \rightarrow \mathbb{Z}_n$ and $\mathcal{H}_2 : \{0, 1\}^* \rightarrow \{0, 1\}^k$ be two collision-resistant hash functions respectively. The AM picks hash generators $u', u_1, \dots, u_k \in_R \mathbb{G}$. The published parameters includes a description of the group \mathbb{G} and of the collision-resistant hash functions $\mathcal{H}_1, \mathcal{H}_2$, along with (A, B_0, \hat{A}) and (u', u_1, \dots, u_k) . Note that the auction manager AM's tracing key is $q \in \mathbb{Z}$.

After receiving the public parameters from the AM, the RM is in charge of checking the bidders' public key and identity as follows:

- The bidder B_i first chooses $x_i \in_R \mathbb{Z}_n$; sets $pk_i = g^{x_i} \in \mathbb{G}$ as its private key, and $sk_i = A^{x_i} \in \mathbb{G}$ as its public key.
- B_i randomly selects an integer $t_i \in_R \mathbb{Z}_n$ to determine the verification information of pk_i : $a_i = \mathcal{H}_1(g^{t_i} \parallel ID_i)$ and $b_i = (t_i + x_i \cdot a_i)$. Then B_i transmits $\{pk_i, ID_i, a_i, b_i\}$ to RM over a secure channel.
- After receiving $\{pk_i, ID_i, a_i, b_i\}$, RM confirms the validity of the bidder's identity and checks whether the following equation holds:

$$a_i \stackrel{?}{=} \mathcal{H}_1((g^{b_i} \cdot pk_i^{-a_i}) \parallel ID_i)$$

If it holds, then $\{pk_i, ID_i\}$ is identified as the valid public key and identity. Otherwise, it will be rejected. After that, RM keeps the relation $\{pk_i, ID_i\}$ secret and publishes pk_i on the BBS.

3.2. Bidding phase

In one round of auction, bidder B_i signs his bid M_i before sending it out. Suppose $S = \{pk_1, \dots, pk_l\}$ is the set of public keys and it defines the ring of public keys. We assume that all public keys pk_i , $1 \leq i \leq l$ and their corresponding private keys sk_i 's are generated by the corresponding bidders, and i^* ($1 \leq i^* \leq l$) is the index of the actual bidder. The signature generation algorithm $Sig(S, sk_{i^*}, M_{i^*})$ is carried out as follows.

1. Compute $\mathcal{H}_2(M_{i^*}, S) = (m_1, \dots, m_k)$. Define $\{f_i\}_{i=1}^l$ as

$$f_i = \begin{cases} 1, & \text{if } i = i^*; \\ 0, & \text{otherwise.} \end{cases}$$

2. For each i , $1 \leq i \leq l$, choose a random exponent $e_i \in_R \mathbb{Z}_n$ and set $C_i = (pk_i/B_0)^{f_i} h^{e_i}$ and $\pi_i = ((pk_i/B_0)^{2f_i-1} h^{e_i})^{e_i}$.
3. Compute $C = \prod_{i=1}^l C_i$ and $e = \sum_{i=1}^l e_i$.
4. Finally, choose $r \in_R \mathbb{Z}_n$ and compute $S_1 = sk_{i^*} \cdot (u' \prod_{j=1}^k u_j^{m_j})^r \cdot \hat{A}^e$ and $S_2 = g^r$.

The signature σ_i of M_i with respect to S is $\{(S_1, S_2), \{C_j, \pi_j\}_{j=1}^l\}$. After generating the ring signature on his bid successfully, B_i will send $\{M_i, \sigma_i\}$ to the AM.

3.3. Winner announcement phase

After the deadline, AM chooses the highest (or the most suitable) bid and runs the verify procedure. If the output is yes, AM accepts the bid as the winning bid. Otherwise, AM repeats the process for the remaining bids. The process of verifying the signature of bid is as follows:

1. Compute $\mathcal{H}_2(M, S) = (m_1, \dots, m_k)$.
2. For each i , $1 \leq i \leq l$, check whether $\hat{e}(C_i, C_i/(pk_i/B_0)) \stackrel{?}{=} \hat{e}(h, \pi_i)$ holds or not. If any of the C_i is invalid, reject. Otherwise, set $C = \prod_{i=1}^l C_i$. Accept if the following equation is satisfied: $\hat{e}(A, B_0 C) \stackrel{?}{=} \hat{e}(S_1, g) \hat{e}(S_2^{-1}, u' \prod_{j=1}^k u_j^{m_j})$

Once a winning bid is determined, AM posts the bid of the winning bidder on the BBS along with the ring signature on this bid.

3.4. Open protocol

If B_i repudiates his bid or simply crashes, AM invokes the open protocol, which is two-party protocol between AM and RM for opening the real identity of the bidder. At the beginning of this protocol, AM checks the validity of the signature and then uses its tracing key $q \in \mathbb{Z}$ and determines if

$$(C_i)^q \cdot B_0 \stackrel{?}{=} pk_i$$

for some i , $1 \leq i \leq l$. If the equation holds at, say when $i = i^*$, then AM sends the pk_{i^*} to RM.

After receiving pk_{i^*} , RM looks up the record (pk_{i^*}, ID_{i^*}) to find the corresponding identity ID_{i^*} meaning that bidder with identity ID_{i^*} is the real bidder. The RM then evicts bidder ID_{i^*} from auction and pk_{i^*} from BBS if this bidder is malicious. Otherwise, if this bidder wins the auction, RM will send (pk_{i^*}, ID_{i^*}) to the AM.

4. Analysis

The security and efficiency of auction protocol is analyzed in this section. It will be shown that the protocol is fair, publicly verifiable and achieves conditional privacy-preserving, unlinkability, and robust.

4.1. Security Analysis

Identity privacy preservation: There is no single authority who can break anonymity.

Given a valid ring signature σ of some message, it is computationally difficult to identify the actual bidder by any participant in the system except the cooperation of RM and AM. If there exists an algorithm which breaks the signer anonymity of the construction in Section 3.2, then the Subgroup Hiding (SGH) assumption would be contradicted [23]. Furthermore, only RM knows the relation between the pk_i and bidder's real identity ID_i . So, only the cooperation of RM and AM can break the bidder's anonymity.

Non-repudiation: No bidder can deny he had submitted his bid.

Given the signature, the AM who knows the tracing key q , can trace the public key of a malicious bidder using the Dispute protocol described in section 3.4. Besides, the tracing process carried by the AM does not require any interaction with the malicious bidder. With the cooperation of RM, the real identity of the malicious bidder can be revealed.

Unforgeability: In our protocol nobody can impersonate any other bidder to make a bid.

According to [23], the ring signature is unforgeable with respect to the insider corruption if Computational Diffie-Hellman (CDH) problem is hard. So, in our proposed scheme, the bid along with the ring signature can only be generated by the valid ring members.

Fairness: Our protocol has fairness of bidder since the bidder is anonymous during the auction.

Fairness of bidder in an electronic auction means that any bid is fairly accepted by AM. Generally, in an electronic English auction, fairness of bidder depends on AM. Our protocol can avoid unfairness, such as AM repudiates any bidding by a certain bidder, because the bidding is done anonymously.

Public verifiability: It is public verifiable that the price of the successful bid is higher than any other bids.

In our protocol, anyone can simulate the procedure to verify the validity of bids using the information on the BBS. Since all the information necessary to decide the auction result is published on the BBS, anyone can verify the auction result.

Unlinkability among plural auctions: It is impossible to link the same bidder among plural auctions.

Unlinkability is the basic property related to ring signature: two ring signatures issued by the same signer are unlinkable in any way, except the very fact that this signer appears in the set of public keys of both ring signatures [1, 3, 9, 15, 23, 31]. So nobody can link two signatures among plural auctions.

Robustness: Malicious cheating and crashing can be recovered.

Misbehavior takes place from time to time as a result of either intentional malicious behaviors (e.g., attacks) or hardware malfunctioning. It is less difficult to prevent misbehavior of unauthorized users of auction protocols (i.e., outsiders) since legitimate users can simply ignore the messages injected by outsiders by means of authentication. This is one reason that we say ring signature is the building block of auction protocols. On the contrary, misbehavior of legitimate users of auction protocols (i.e., insiders) is more difficult and complex to prevent, the reason being that insiders possess the legitimate public/private key pairs to perform authentication with peer bidders who can be easily tricked into trusting the insiders. Consequently, the insiders' misbehavior will have much larger impact on the network and be more devastating. Fortunately, the opening phase can be employed to detect such misbehavior and misbehaving users will be evicted accordingly.

One-time registration: Any bidder can take part in plural auctions as a valid bidder in one-time registration of public key, maintaining anonymity for RM, AM, and other bidders.

Note that the honest bidder can get the public key of ring members (a set of bidders) required to generate the ring signature arbitrarily from the BBS without any interaction with any other bidders, RM or AM in the system. So, the honest bidder can take part in plural auctions in one-time registration.

4.2. Efficiency Analysis

In our protocol, the computational costs and communication overheads on AM and RM are not stringent since these entities are resource-abundant in nature. We are interested in the computational costs and communication overheads at bidders which are least powerful in our system. We use table 2 to show the performance analysis of our protocol and [33]. For convenience, we define the following notations: T_e (the time for one exponentiation computation); T_m (the time for one modular multiplication computation); T_i (the time for one inverse computation); T_h (the time for executing the adopted one-way hash function); T_{Enc} (the time for executing the encryption function); T_{Dec} (the time for executing the decryption function). The parameter l and k are

used to denote the number of public keys in the generation of ring signature and the length of the output of hash function \mathcal{H}_2 respectively. It is obvious that our proposed protocol possesses the advantages of [33] due to the computation efficiencies and communication rounds.

Table 2: The comparison of efficiency

	Xiong et al.'s scheme[33]	Our scheme
Initial Phase	$T_e + T_{Enc} + T_{Dec}$	$3T_e + T_h + T_m$
Pre-Bidding Phase	$(3l - 2)T_e + lT_h + (2l + 1)T_m$	
Bidding Phase	$(3l - 2)T_e + lT_h + (2l + 1)T_m$	$T_h + (5l + k + 2)T_e + (5l + k + 1)T_m + 2lT_i$
Winner announcement Phase	$(3l - 2)T_e + lT_h + (2l + 1)T_m$	
Rounds	4	2

In addition, our protocol does not need to maintain a *black list* which is the list of evicted participants, different from the auction protocol based on group signature [30, 24, 22]. Furthermore, our protocol does not require every remaining bidder to renew their secret membership key and updating public information. Thus, our protocol is more practical than [30, 24, 22].

5. Conclusions

A privacy preserving English auction protocol with round efficiency based on a modified ring signature has been proposed in this paper. We demonstrate that proposed protocol does not only provide conditional privacy, a critical requirement in English auction protocols, but also able to improve efficiency in terms of communication round complexity and identity tracking in case of a dispute. Meanwhile, our proposed solution can achieve one-time registration: that is to say, the bidder can take part in plural auctions in one time registration.

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